Airport ASF Mapping Methodology Update

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Abstract

In 2001, the Volpe National Transportation Systems Center completed an evaluation of GPS vulnerabilities and the potential impacts to transportation systems in the United States. One of the recommendations of this study was for the operation of backup system(s) to GPS; Loran-C was identified as one possible backup system. The Federal Aviation Administration (FAA) has been leading a team consisting of members from industry, government, and academia to evaluate the future of Loran-C in the United States. In a recently completed Navigation Transition Study, the FAA concluded that Loran-C, as an independent radionavigation system, is theoretically the best backup for the Global Positioning System (GPS). However, in order for Loran-C to be considered a viable back-up system to GPS, it must be able to meet the requirements for non-precision approaches (NPA's) for the aviation community, and the Harbor Entrance and Approach (HEA) requirements for the maritime community.

A significant factor limiting the accuracy of a Loran system is the spatial and temporal variation in the times of arrival (TOAs) observed by the receiver. A significant portion of these variations is due to the signals propagating over paths of varying conductivity; these TOA corrections which compensate for propagating over non-seawater paths are called additional secondary factors (ASFs). Hence, a key component in evaluating the utility of Loran as a GPS backup is a better understanding of ASFs and a key goal is deciding how to mitigate the effects of ASFs to achieve more accurate Loran-C positions while ensuring that the possibility of providing hazardous and misleading information (HMI) will be no greater than $1\text{x}10^{-7}$.

The future of Loran for aviation is based on multi-station, multi-chain, all-in-view, DSP-based receivers observing TOA measurements with H-field antenna technology. For an aviation receiver, the approach to mitigate propagation issues under study is to use a single set of ASF values (one for each Loran tower) for a given airport. This value may have seasonal adjustments applied to it. The Loran receiver will use this set of static ASF values to improve position accuracy when conducting a non-precision approach (NPA). A Working Group is currently developing the procedures to be used to "map" the ASF values for an airport. The output of the Working Group will be a set of tested and documented procedures for conducting an airport survey; these procedures can then be followed to survey airports nationwide. The draft procedure has been tested during data collection at airports in Maine and Ohio. This paper discusses the results of this data collection: how well the spatial variation seen on the ground matches the BALOR model prediction and the implications of this on the proposed procedure, an analysis of how many ASFs should be required to meet RNP 0.3 for each airport based on geometry and ASF variation in the area, and results of the position accuracy obtained by the aircraft flying approaches when using the airport ASF values.

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Background / Introduction

Contrary to what some may believe Loran-C is still alive and in use worldwide. The United States is served by the North American Loran-C system made up of 29 stations organized into 10 chains (see Figure 1); coverage for the rest of the world is shown in Figure 2.
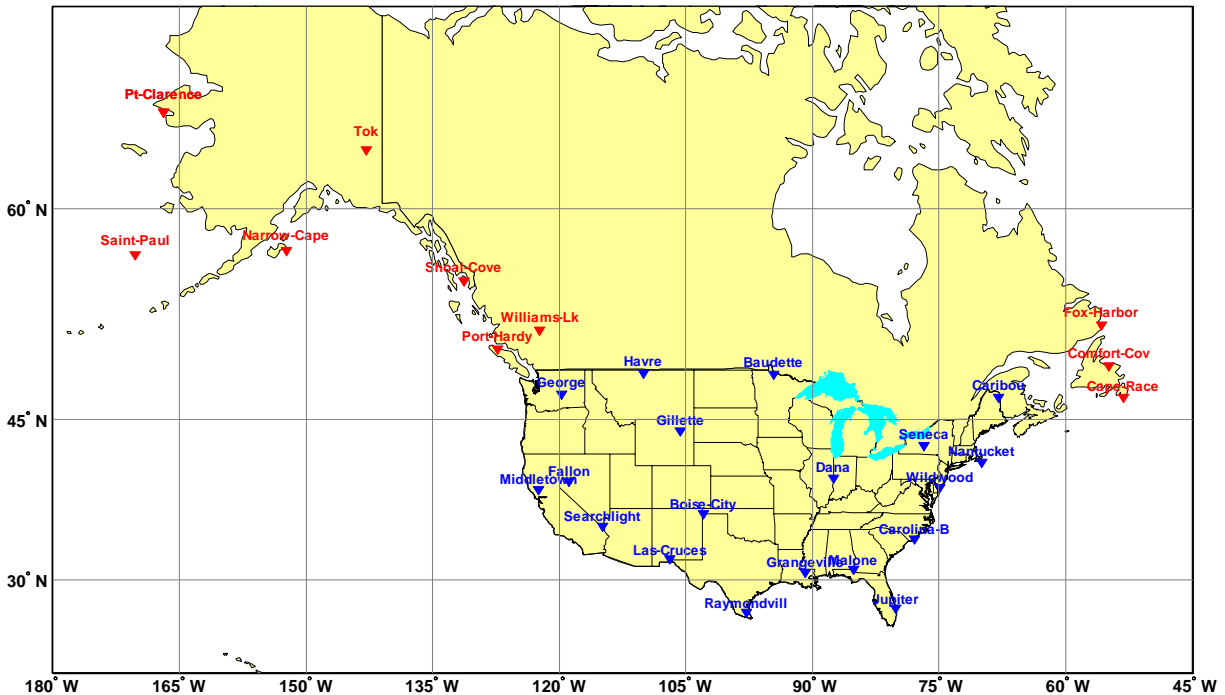

Figure 1 – North American Loran-C System, blue = new TFE stations.

Figure 2 – Worldwide Loran coverage.

Given the ubiquity and quality of service available from the Global Positioning Service (GPS), one might wonder of what use is a system that has been operational since the 1970's? The answer is that Loran is an excellent backup system for GPS. As discussed in many sources, such as the Volpe vulnerability study [1], GPS is vulnerable to both intentional and unintentional jamming. Since Loran is a totally different system and subject to different failure modes than GPS, it can act as an independent backup system that functions when GPS does not. The Federal Aviation Administration (FAA) observed in its recently completed Navigation and Landing Transition Study [2] that Loran-C, as an independent radio navigation system, is theoretically the best backup for GPS; however, this study also observed that Loran-C's potential benefits hinge upon the level of position accuracy actually realized (as measured by the 2 drms error radius). For aviation applications this is the ability to support non-precision approach (NPA) at a Required Navigation Performance (RNP) of 0.3 which equates to a 2 drms position error of 307 meters and for marine applications this is the ability to support Harbor Entrance and Approach (HEA) with 8-20 m of accuracy.

A significant factor limiting the accuracy of a Loran system is the spatial and temporal variation in the times of arrival (TOAs) observed by the receiver. A significant portion of these variations is due to the signals propagating over paths of varying conductivity; the TOA corrections which compensate for propagating over non-seawater paths are called additional secondary factors (ASFs). Hence, a key component in evaluating the utility of Loran as a GPS backup is a better understanding of ASFs and a key goal toward ensuring Loran's future is deciding how to mitigate the effects of ASFs to achieve more accurate Loran-C positions while ensuring that the possibility of providing hazardous and misleading information (HMI) will be no greater than $1x10^{-7}$.

The future of Loran for aviation is based on a multi-station, multi-chain, all-in-view, DSP-based receiver observing TOA measurements with an H-field antenna. For such an aviation receiver, the approach under consideration to mitigate the effects of propagation issues on accuracy is to use a single set of ASF values (one for each Loran tower) for a given airport. (In the event that local ASF variations are too large to meet the accuracy targets with a single set of ASF values, it is envisioned that an additional set of ASF values will be used with the user's receiver interpolating between them.) While ASFs also exhibit seasonal variation, the current approach is to choose the ASF value for each station in the middle (the median) of the seasonal range and to absorb the variation within the navigation system's error budget. The Loran receiver would use this set of static ASF values to improve position accuracy when conducting a non-precision approach (NPA). The Loran Evaluation Panel Working Group on ASFs is currently developing the procedures to be used to "map" the ASF Correction Estimates (ACE) for an airport. The output of the Working Group will be a set of tested and documented procedures for conducting an airport survey; these procedures can then be followed to survey airports nationwide.

In a presentation at the 2005 ION June meeting, we proposed procedures and a testing methodology to validate those procedures [3]. One of the runways at Walker Field in Grand Junction, CO, was used as an example in that presentation. Equipment to be used in the testing, and the error budgets for that equipment as well as the ASF methodology itself were also discussed. This paper reviews and updates our proposed methodology and then presents results for airports in Maine and Ohio.

Proposed Methodology

Once an airport and its specific runways have been identified, the methodology consists of two parts:

1. computational and simulation work to establish locations for field tests
2. field measurements

We describe both of these components below. Note that we have the working assumption that the BALOR ASF prediction software (described in [4]) provides a reasonable assessment of the real world conditions. One of the goals of the field measurement work of the working group is to validate this assumption.

Methodology Part I – Computation/Simulation

The first task in assessing the ASFs for a specific airport consists of identifying those Loran stations available for use in the position solution and to compute the predicted ASFs for the area using the BALOR software. BALOR is a software model developed by the University of Wales at Bangor and modified under an FAA-funded contract for the Loran Evaluation team (further modifications and improvements to the software have been made by Working Group members at Ohio University). This software is designed for calculating predicted ASFs using the Monteath and Waite methods [5-7]. It uses a terrain elevation database (DTED Level 1 format), a ground conductivity database (from the FCC), and a coastline database (World Vector Shorelines) for the ASF computations. The BALOR software computes ASF values on evenly spaced grid points; for our analysis and simulations we computed these values for a grid spacing of 0.001 degrees both in latitude and longitude. Additional details on our use of the software are contained in [8, 9]. Currently, the runway end is used as the static point for the local ASF value.

The primary goal of computing the ASF grids is to determine whether one set of ASFs is sufficient for each approach path or if multiple sets are needed. This is accomplished by considering the worst case ASF differences, the station geometries, and the expected signal to noise ratios. Since this only takes into account predicted ASFs, not model errors and other noise sources, we also simulate the position solution for comparison to the maximum desired value of 120 meters[1]. To simulate time of arrival (TOA) data using these grids, for a specific latitude/longitude position we generate the TOA as:

$$TOA_{sim} = TOA_{pred} + ASF_{pred} + E_{delay} + Noise$$

Here, TOA_{pred} is the predicted arrival time given the precise distance from the corresponding Loran tower to the desired location based on an all-seawater propagation path (this includes the primary and secondary factors usually mentioned for Loran TOAs), ASF_{pred} is the bilinear interpolation of the BALOR ASF grid at that location, E_{delay} is the published emission delay for the station relative to the Master, and Noise combines all potential noise sources. For the aviation simulation, we model two noise sources:

- Directional variation due to antenna issues – a typical one sigma (standard deviation) value is 100 nsec.

- Receiver channel noise – in the range of 25-100 nsec depending upon the station SNR.

This examination of the worst case effects of ASF differences focuses on the approach paths for each runway (out to 10 miles from the runway end); the simulation examines a subset of points along the approach focusing on potential bad spots due to ASF differences. In our earlier study of this computational component of the methodology [3], we also included a noise term (with 100 nsec standard deviation) to account for ASF variation as a function of altitude (BALOR computes ASFs at fixed AGL while an approach can range through 4000 ft of altitude). Here, we drop this term as it is currently under study (see our companion paper in this Proceedings [10]).

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[1] Although the accuracy constraint to meet RNP 0.3 is 307m, due to other error components such as seasonal variation and transmitter noise, the position domain bound has been set at 120m for spatial error.

Methodology Part II – Field Tests

The purpose of this second part of the methodology is to validate the analysis above by measurements in the field. To remove temporal variations in ASFs, either due to system errors or selected environmental effects (e.g. weather, season), a static monitor is set up at the airport collecting TOAs for all Loran stations of interest during the entire test period. A second TOA measurement system is employed to measure TOAs at the selected test sites along the approaches, typically at 1-2 mile spacing from the runway end to 10 miles out. Further, multiple approaches are flown (typically 5) to collect TOA data at approach altitude. The airport TOAs and any system timing offsets (available in data captured at the Loran stations) are subtracted from these TOAs to remove any temporal variation; the residual is a combination of the spatial ASF and noise. We have several notes:

- The desired test site locations on the ground may not be reachable (no roads, private property, etc.). We expect to be able to reach on land points to within 0.5 miles crosstrack from the approach centerline and 0.5 miles along the approach path itself; points over water are not tested.

- Sufficient data must be collected at each ground test site to average out noise effects to achieve an ASF measurement accuracy of a standard deviation of 25 nsec. or less. This collection time is a function of the station rate, the received SNR, and must recognize that the differencing of TOAs with the static monitor doubles the effective receiver noise (hence, 4 times as many samples are required).

- While the aircraft data will be noisier, we intend to use it, in a post-process mode, to validate both the accuracy of BALOR and the overall methodology. By post-process mode, we mean that measured TOAs will be corrected using the ACE value for the airport. Further, when assessing the resulting position accuracy, we will attempt to remove both airplane dynamics and the Loran receiver averaging window.

- Further, data collection with a second static monitor nearby (e.g. at a local airport) will be employed to study the geographic stability of the temporal variation.

Our basic data collection system is outlined in Figure 3; details can be found in our earlier papers [3, 11]. It consists of both E and H field Loran receivers for measuring TOAs. A rubidium clock is used to provide a common, stable, 10 MHz reference to all equipment. A L1/L2 GPS receiver is used to provide a reference position track and a 1PPS synchronized to UTC for timing measurements and to provide long-term stability to the rubidium clock. Digital counters are used to measure the time difference between the PCI strobes from the Loran receivers and the UTC 1PPS to enable the ASF calculations. Not shown is the weather station to collect environmental data. All data is collected on a laptop running Alion's RcvrIntegration software. The mobile data collection system for the chosen ground sites is mounted in a van with mast antenna as shown in Figure 5; flight verification is recorded by flying approaches using the FAATC's Convair 580 shown in Figure 4.
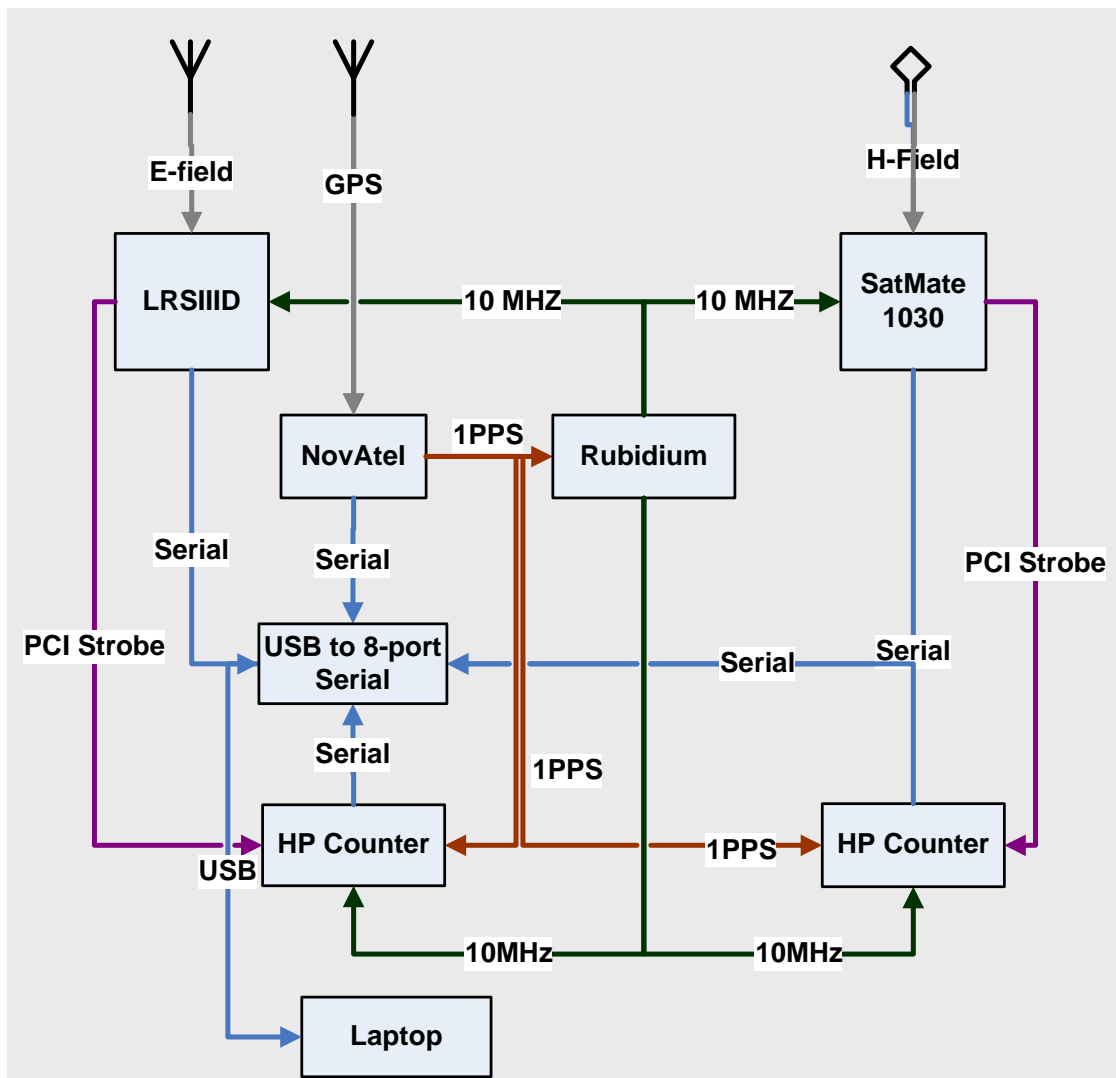
Figure 3 – Block diagram of the data collection system.

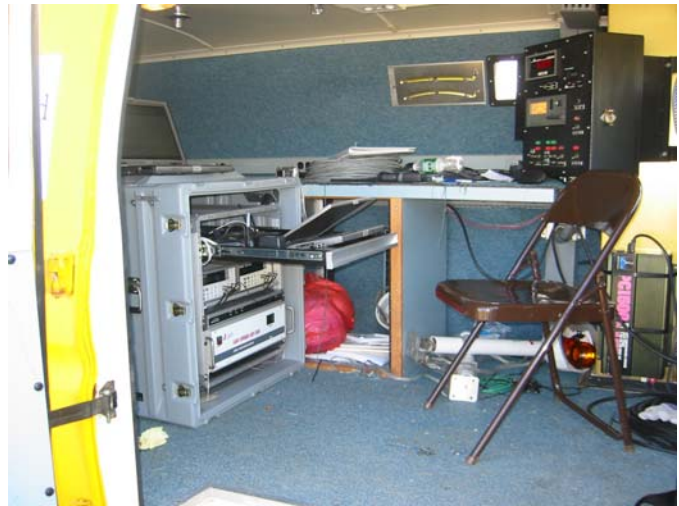**Figure 4 – The FAATC Convair 580 employed for flight verification.**

Figure 5 – The FAATC test van employed for ground data collection.

Recent Field Tests

Since our June 2005 presentation [3] we have begun field testing of the proposed methodology. Our test plan consists of four components:

- Ground measurements of ASFs at selected locations along approach paths (to validate data used for the simulations)

- Flight verification of the simulated RNP 0.3 performance (to validate the results of the simulations)

- Long baseline flights (to directly assess BALOR accuracy)

- Measuring ASFs versus altitude (to bound any variation present in the 4000 ft altitude range)

During July-September 2005, data was collected for airports in Maine and Ohio to achieve the first two goals; additional data collection is planned for the latter two (see our companion paper on altitude effects in these Proceedings [10]). We present the results next. The approach at this point is quite similar to the example in [3].

Portland Maine

We first consider Portland International Airport (PWM) which has 4 runways (IDs 11, 29, 18, and 36) as shown in Figure 6 (the box extends the approaches out 10 miles; +'s mark points along each approach). For a Loran solution, we consider the three stations within 1000 km: Caribou, Nantucket, and Seneca. Figure 7 shows the relative locations of Portland and these Loran towers.

Figure 6 – Portland International Airport's runways and approach pattern.
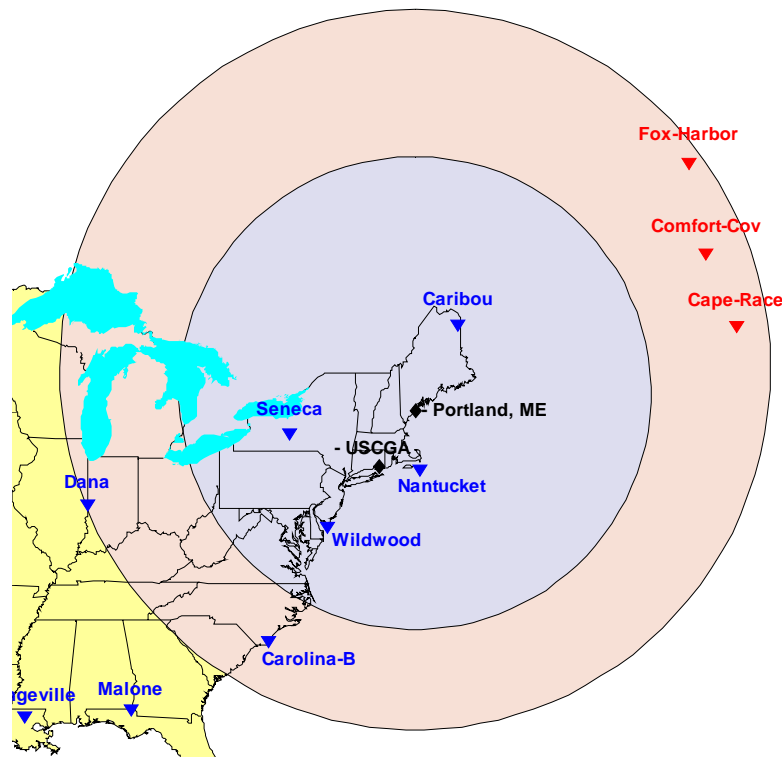

Figure 7 – Loran towers around Portland. Circles are at 1000 and 1500 km.

Next, we employ the BALOR software to estimate the ASFs for these stations; as an example, Figure 8 shows the ASFs for Loran station Caribou (the approaches and coastlines are overlaid on this contour plot for convenience of viewing). Of greater value are the differences in the predictions from the value at the airport (the static ACE value used by the receiver) at points along the runway approaches. For PWM, we concentrate on runway 11 (approaching from the west) and show in Figure 9 the ASF differences for the three Loran stations; between 4 and 6 miles out we experience the greatest ASF variation of approximately 250 nsec. The sharp decline in the Nantucket predictions appears to be due to the propagation path traversing Cape Cod close to the runway and Cape Cod Bay further out as shown in Figure 10.

Figure 8 – BALOR for Caribou about PWM.

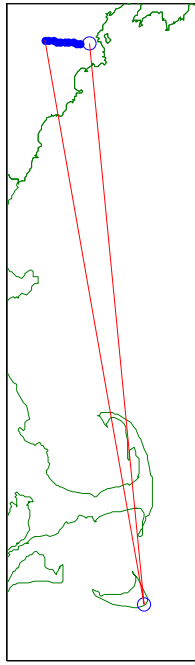**Figure 9 – BALOR differences along the approach for runway 11.**

Figure 10 – Geometry from Nantucket to PWM runway 11.

With these ASF predictions we can compute the effect of the ASF mismatch on position solutions for a user implementing ASF correction using the ACE value. Specifically, we predict the TOA from:

$$TOA_{expected} = TOA_{pred} + ASF_{pred} + E_{delay}$$

(the only difference from the simulation TOAs is the lack of noise). We then subtract out the ASF estimate, ACE,

$$TOA_{adjusted} = TOA_{pred} + ASF_{pred} + E_{delay} - ACE$$

and compute the position using these values. Figure 11 shows, as the solid blue line, the performance of this approach as horizontal error (total error, not just cross track) due to the ASF mismatch and the underlying Loran geometry (the HDOP). We note that the largest error corresponds to the largest ASF difference at approximately 5 miles out. We note that the error from ASF mismatch for one set of ACE values is limited to 50 meters for most of the approach.

Adding noise (directional and receiver noise) as described above, typical position performance results are overlayed on Figure 11 of the theoretical performance. The blue dots show the average horizontal error for a subset of points uniformly spaced along the approach plus the point at the runway (distance 0); the blue triangles show the 95% range. We note by looking at the runway end point that for the existing station geometry and power levels, Loran (with perfect ASF correction) suffers from approximately 40 meters of error (on average); the ASF mismatch further out along the approach adds to this.
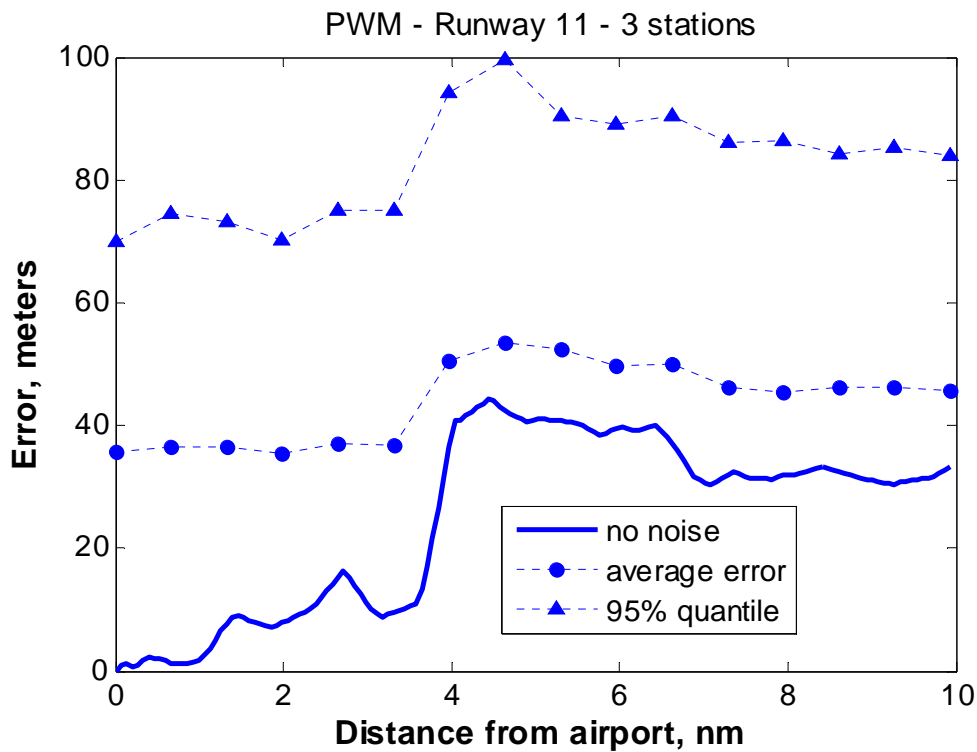
Figure 11 – Position performance along approach to runway 11.

To test our simulation results, the Convair 580 flew five approaches along runway 11, collecting Loran (H-field) and GPS (used as truth) data; the resulting position error is compiled in Figure 12. The red points are typical Loran position data; off by ¼ mile. The blue and green are total and cross track errors, respectively, for a "corrected" Loran receiver. Correction, in this case, consists of using the ACE value to correct some of the ASF along with time-shifting the GPS positions corresponding to specific sets of TOAs to account for airplane dynamics and the averaging time of the receiver. (In other words, since the Loran receiver averages pulses over a time window to produce a set of TOAs, and since the plane moves along its approach during that averaging window, the TOA produced at a particular point in time corresponds to an average of the TOAs over prior locations of the plane. We "correct" this as best we can based upon knowledge of the speed of the plane and the averaging time of the receiver.) Unfortunately, the results of Figures 11 and 12 do not match all that well. Since the data shown in Figure 11 is based upon BALOR predictions, it is only as good as the BALOR model; work is in progress to evaluate the accuracy of the BALOR model.
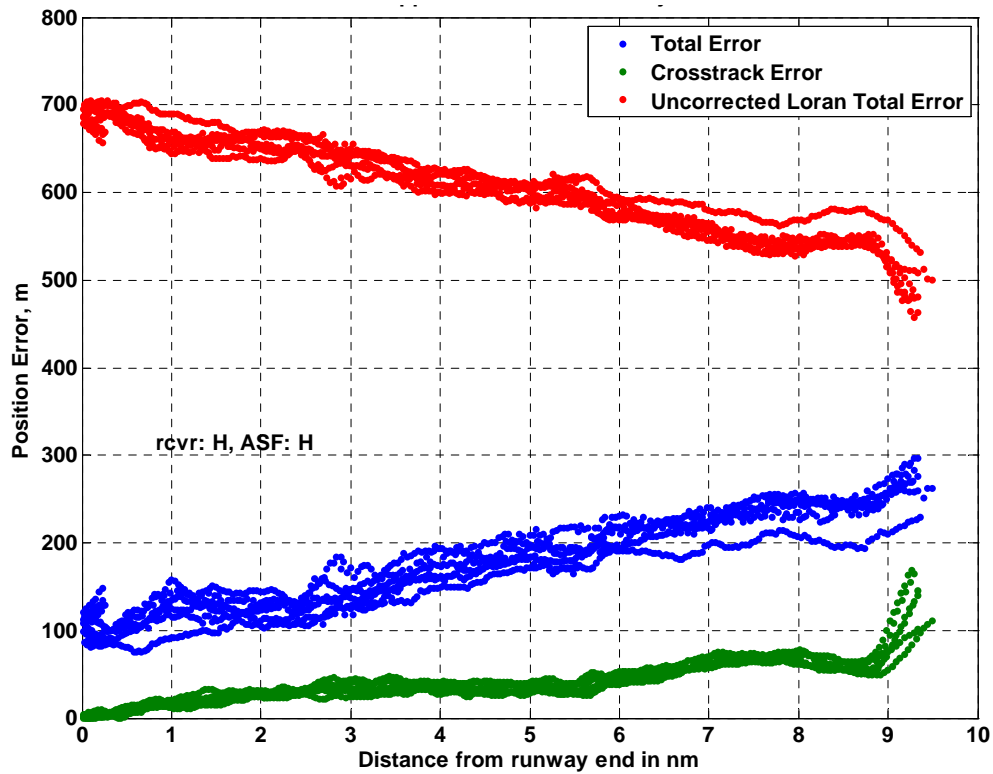
Figure 12 – Measured position domain error along approach to PWM runway 11.

Lorain Ohio

We consider Lorain County Airport (LPR) which has 2 runways (IDs 7 and 25) as shown in Figure 13. For a Loran solution, we consider six stations: Baudette, Carolina Beach, Dana, Grangeville, Nantucket, and Seneca. Figure 14 shows the relative locations of LPR and these Loran towers.
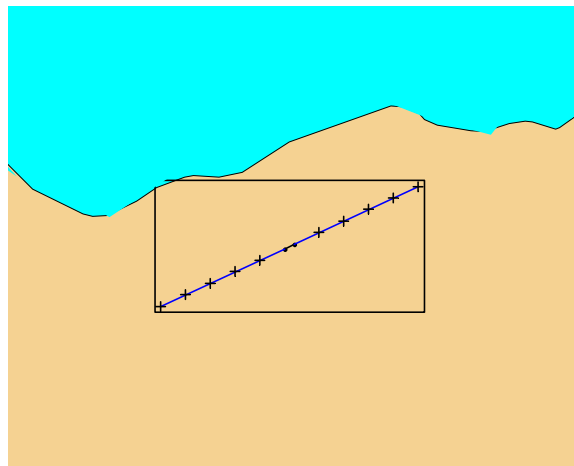

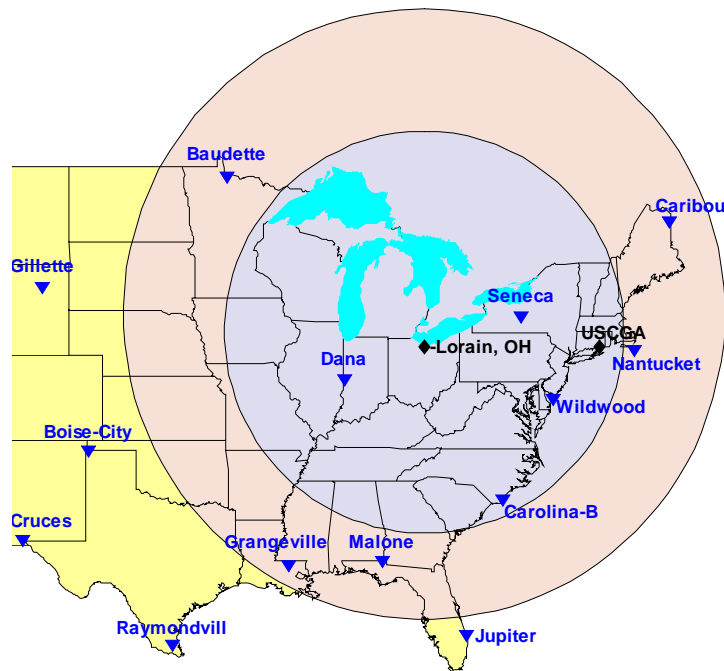**Figure 13 – Lorain County Airport's runways and approach pattern.**

Figure 14 – Loran towers around LPR. Circles are at 1000 and 1500 km.

In general, BALOR estimates of the ASFs for these stations show little variation over the airport region; as an example, Figure 15 shows the ASF for Loran station Dana (a spread of only 120 nsec over the entire area). The differences in the predictions from the value at the airport (the static ACE value used by the receiver) along the approach to runway 7 appears in Figure 16. We see a total spread of approximately 100 nsec at 10 miles out, particularly between Dana and Seneca, which should contribute to the position error due to ASF mismatch. Figure 17 shows that the position error along the approach due to ASF correction (ACE) mismatch alone (the solid blue line) appears to remain well below 20 meters. Adding noise, we see in Figure 17 (via simulation) average position errors of 40-50 meters and a 95% point below 100 meters. As was done for PWM, the Convair flew five approaches into LPR measuring TOAs. The Loran position errors are shown in Figure 18 (raw, "corrected" total, and "corrected" cross track). In this relatively benign ASF environment, there appears to be reasonable agreement between the simulation and measured performance.
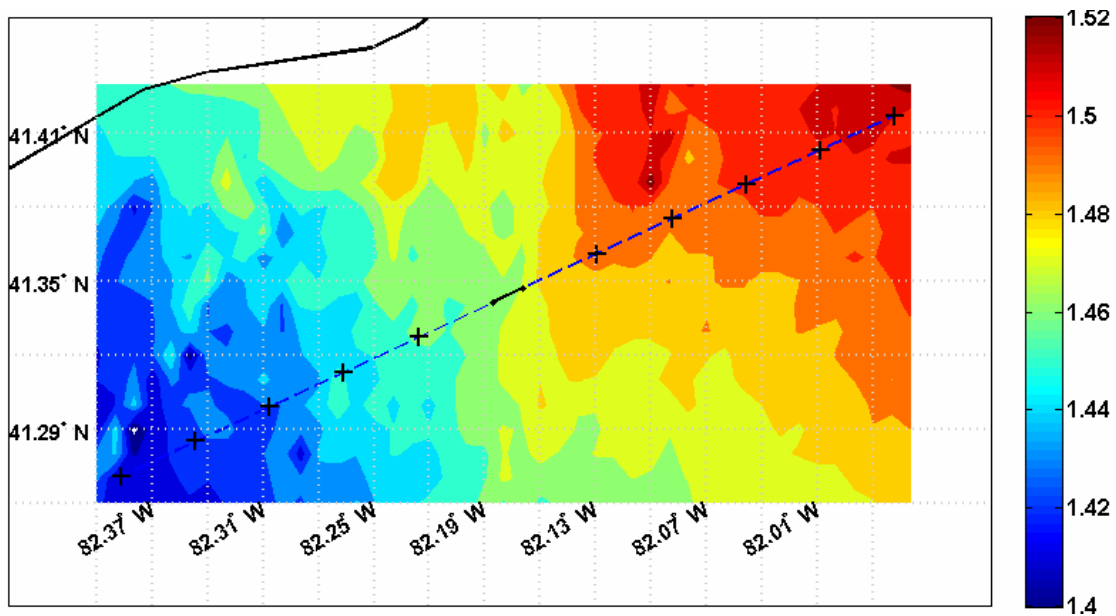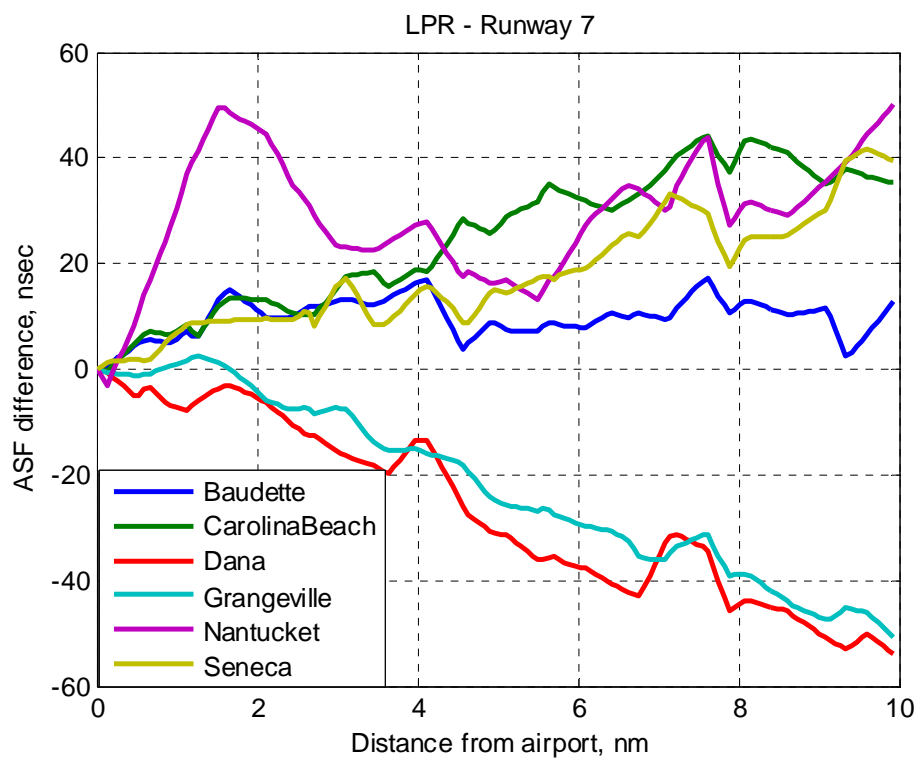
Figure 15 – BALOR for Dana about LPR.

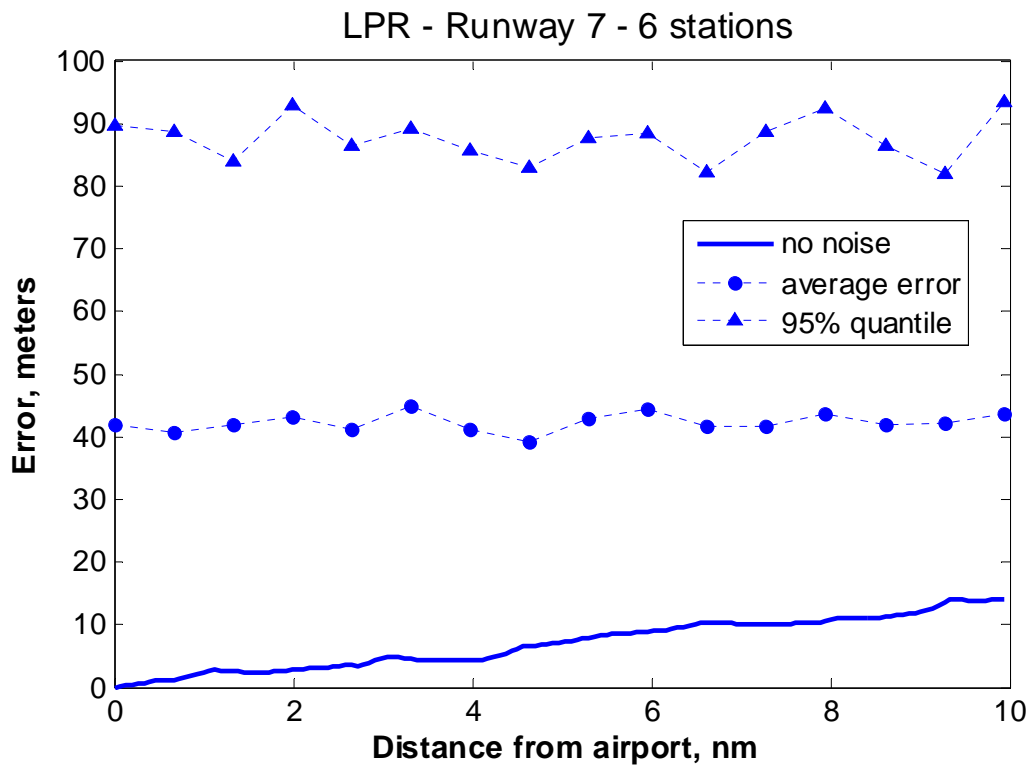**Figure 16 – BALOR differences along the approach for runway 7.**

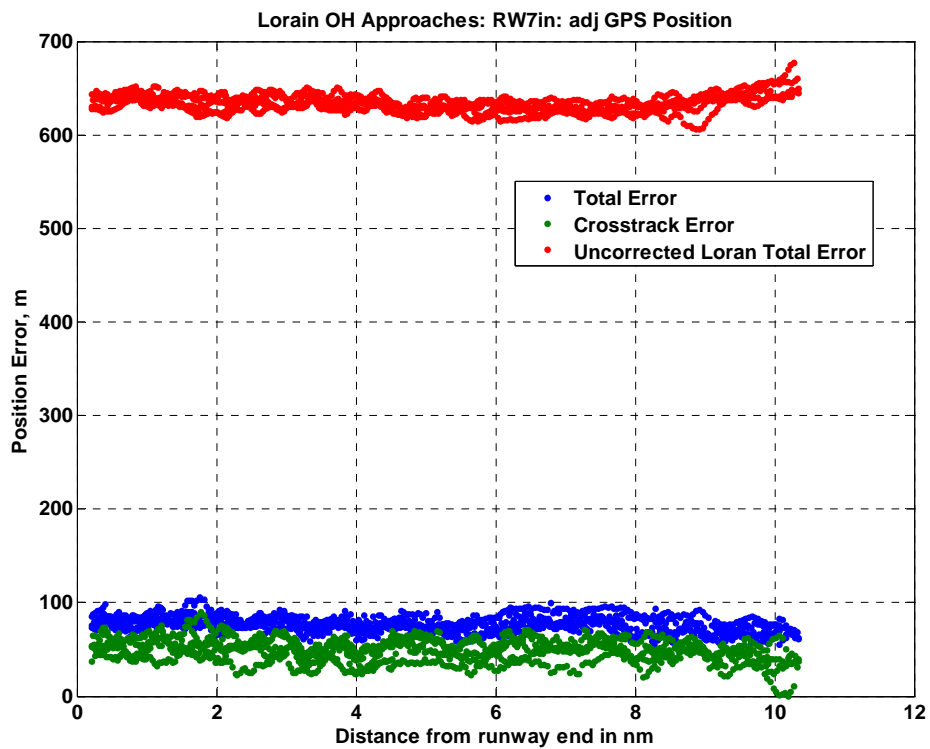**Figure 17 – Position performance along approach to runway 7.**

Figure 18 – Measured position performance along approach to runway 7.

Conclusions / Future work

At this time, our test equipment is assembled and tested, the test plan described above is complete, and field testing has begun. While we have made minor changes to our methodology, the majority of our effort is on validating the simulation results (using BALOR ASF estimates) to data from actual ground and air measurements. Our future efforts include:

- Continue analysis of the Maine and Ohio data – the results to date are inconclusive.

- Collect (scheduled for November 2005) and analyze long baseline measurements – long baseline measurements (in-flight TOA data) will be collected along flight paths to/from selected Loran towers to assess BALOR accuracy at large scale (> 1000 km) prediction of ASFs. Flight paths that will provide a variety of propagation paths to/from the Loran towers: all-seawater, all-land, and mixed seawater and land, are planned. We are planning to fly radials (at 5000 ft AGL) to/from the towers so as to keep the propagation paths fixed. Data will be collected using both E and H field antennas. Post-processing will include the computation of ASFs along the radial paths (subtracting out system timing information from the station TFE as before) and comparison of the measured ASFs and signal strengths to BALOR predictions.

- Continue to fix and enhance the BALOR software.

- Add TFE data to measurements to get actual ASF.

- Study altitude issue – see our companion paper [10] for details.

Acknowledgments

Disclaimer and Note

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, or any agency of the U.S. Government.

Biographies

Peter F. Swaszek is a Professor of Electrical and Computer Engineering at the University of Rhode Island. He received his Ph.D. in Electrical Engineering from Princeton University. His research interests are in digital signal processing with a focus on digital communications and navigation systems.

Gregory Johnson is a Senior Program Manger at Alion Science & Technology, JJMA Maritime Sector. He heads up the New London, CT office which provides research and engineering support to the Coast Guard Academy and R&D Center. He has a BSEE from the USCG Academy (1987) a MSEE from Northeastern University (1993) and a PhD in Electrical Engineering from the University of Rhode Island (2005). Dr. Johnson is a member of the Institute of Navigation, the International Loran Association, the Institute of Electrical and Electronics Engineers, and the Armed Forces Communications Electronics Association. He is also a Commander in the Coast Guard Reserves.

Richard Hartnett is Head of the Engineering Department at the U.S. Coast Guard Academy (USCGA). He graduated from USCGA with his BSEE in 1977, and earned his MSEE from Purdue in 1980, and his

PhD in Electrical Engineering from University of Rhode Island in 1992. He holds the grade of Captain in the U. S. Coast Guard, and has served on USCGA's faculty since 1985. He is the 2004 winner of the International Loran Association Medal of Merit.

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